ULTIMA

ULTIMA Update - Ultra Light Telescope, Integrated Missions for Astronomy

NGST Technology Challenge Review
Goddard Space Flight Center
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Outline

- Background
- Benefits of very large telescopes for space astronomy
- Primary Ultima concept
- Segmentation effects
- Correction optics and misalignment tolerances with spherical primary
- Dynamic alignment/pointing/scanning module

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Benefits of Large Filled Apertures

- Larger light gathering capability for faint object detection (~ A)
- Improved resolution for differentiating nearby objects (~1/D)
- Reduced integration time for zodiacal light rejection (~1/A^2)
- Larger field of view and more easily implemented phase coherence than sparse arrays

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Previously constrained by monolithic construction and launch vehicle limitations

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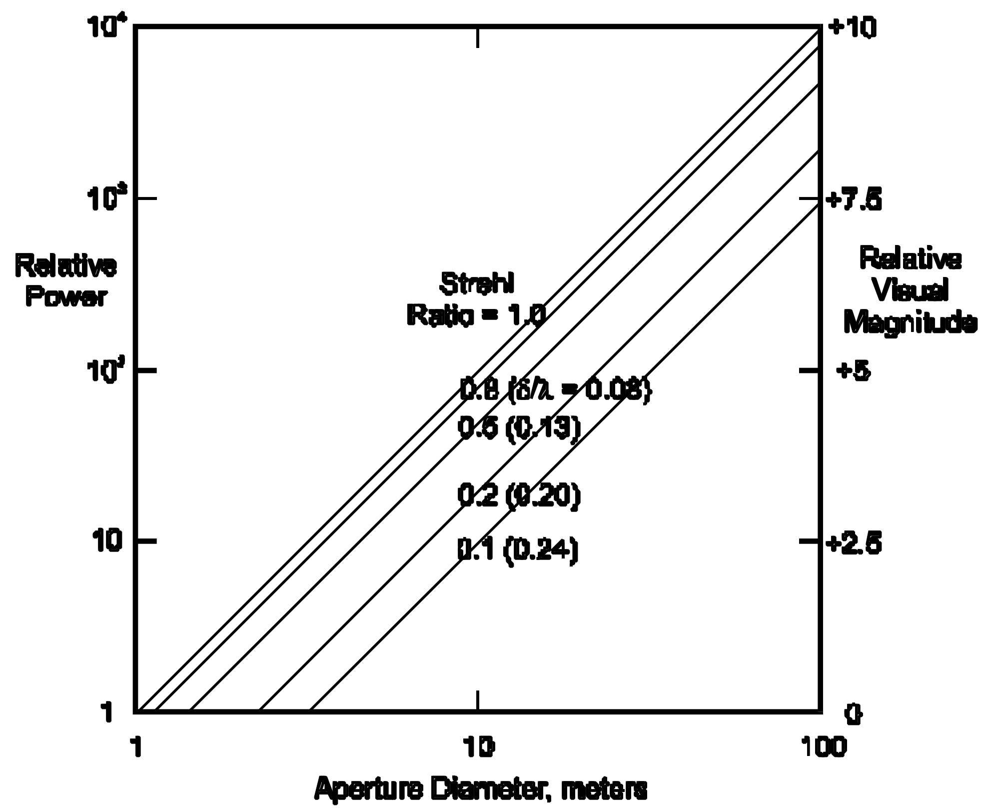
Light Gathering



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Zodiacal Light

Coherent signal photons = $\Phi_s\, A\, \tau / h\nu$

Incoherent zodiacal photons into resolution area $(\lambda F)^2/A$

$$= \varphi_z\, \pi\theta^2\, A\tau/h\nu\; (\lambda F)^2/A/(\pi\theta^2 F^2) = \varphi_z\, \lambda^2 \tau/h\nu$$

With statistical averaging over integration time τ:

$$S/N = \Phi_s\, A\, \tau/h\nu \,/\, \sqrt{[\varphi_z\, \lambda^2 \tau/h\nu]} = \Phi_s A \sqrt{\tau/(\varphi_z \lambda hc)}$$

Thus, $\tau A^2/\lambda = [(S/N)/\Phi_s]^2\, \varphi_z hc$

The integration time required for zodiacal light rejection is inversely proportional to the square of the collecting area if the mean background can be removed

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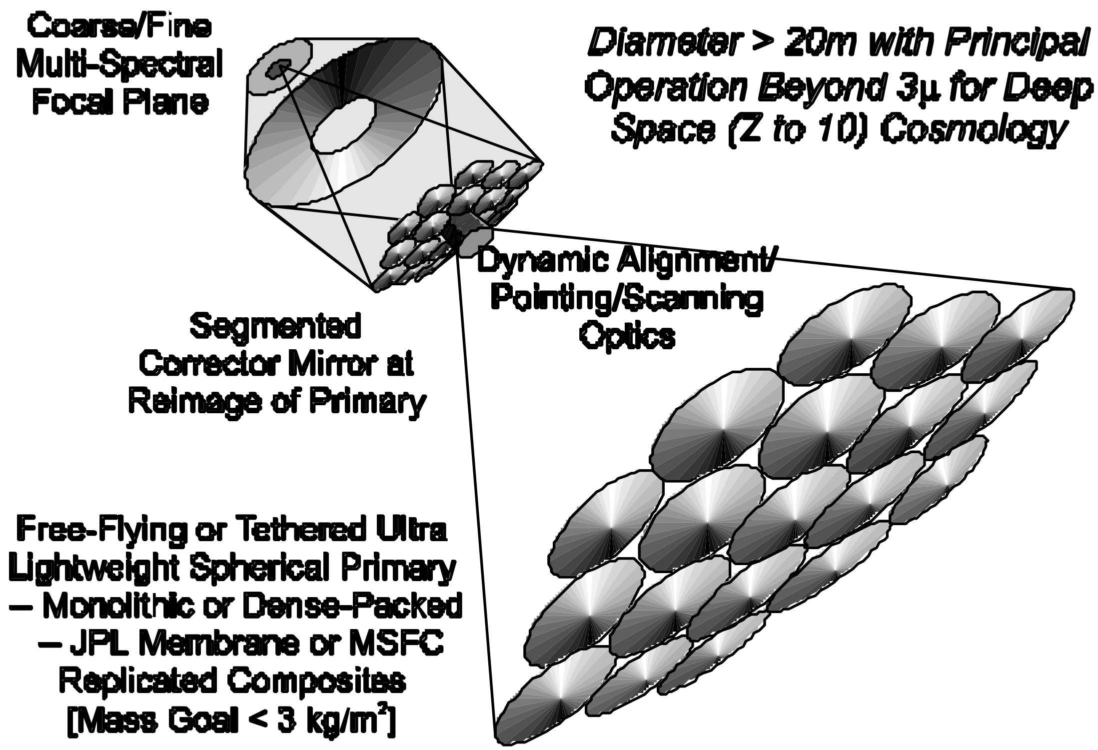
Telescope Concept



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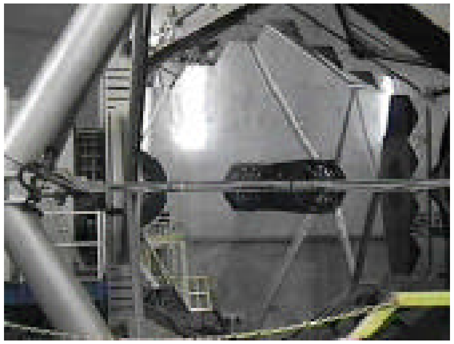
Segmented Telescopes

Keck Telescopes

Twin 10 meter telescopes on Mauna Kea in Hawaii

36 1.8 meter parabolic segments

93M$ Keck I, 78M$ Keck II



Hobby - Eberly Telescope

11 meter Arecibo-type telescope at McDonald Observatory in west Texas

91 1.0 meter spherical segments

13.5M$ (completion in late ‘97)

Primary mirrors with radiotelescope-type structures and many actively-controlled segments

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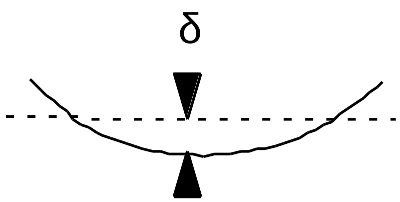
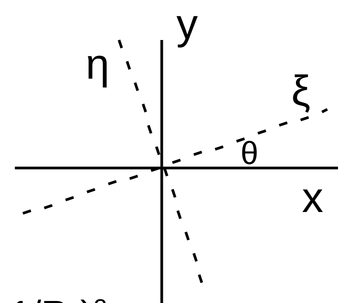
Fitting Segments to Curved Surfaces



Mirror surface $y = \delta_0 + x^2/2R_x + y^2/2R_y$

Reference surface $y = \xi^2/2R_\xi + \eta^2/2R_\eta$



Optimum $\delta_0 = - d^2/32\ (1/R_x+1/R_y-1/R_\xi-1/R_\eta)$

Mean square difference $\langle\delta^2\rangle = 1/3\ (d^2/32)^2\ [(1/R_x+1/R_y-1/R_\xi-1/R_\eta)^2$

$+\ 2(1/R_x-1/R_y-1/R_\xi+1/R_\eta)^2 + 8(1/R_x-1/R_y)(1/R_\xi-1/R_\eta)\sin^2\theta]$

For spherical segments: $\langle\delta^2\rangle = 1/3\ (d^2/32)^2\ [(2/R-1/R_\xi-1/R_\eta)^2 + \underbrace{2(1/R_\xi-1/R_\eta)^2}_{\textit{astigmatic term}}]$

Flats must be very small to fit a curved surface (R>36 m for d =1 cm & δ_{RMS}<0.1μ)

Astigmatic term requires aspheric surfaces for aspheric references

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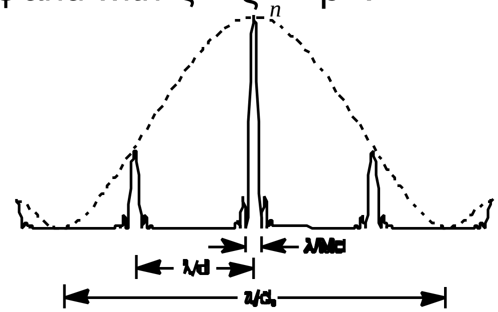
Basic Fraunhofer equation for diffraction: $$I(\vec{x},0)=\left|\frac{1}{\lambda z}\iint\sqrt{I(\vec{\xi},0)}\,e^{i\varphi(\vec{\xi},0)}e^{i\frac{2\pi}{\lambda z}\vec{x}.\vec{\xi}}\,d^2\vec{\xi}\right|^2$$

For identical subapertures with piece-wise uniform I and φ and with $\vec{\xi}=\vec{\xi}_n+\vec{\rho}$:

$$I(\vec{x},0)=\left|\sum_{n=1}^{N}\sqrt{I(\vec{\xi}_n,0)}\,e^{i\varphi(\vec{\xi}_n,0)}e^{i\frac{2\pi}{\lambda z}\vec{x}.\vec{\xi}_n}\right|^2\left|\frac{1}{\lambda z}\iint e^{i\frac{2\pi}{\lambda z}\vec{x}.\vec{\rho}}\,d^2\vec{\rho}\right|^2$$

Discrete Fourier Transform with repeated behavior

Subaperture point spread function



Far-field is composed of multiple identical fields and peaks determined by the configuration and illumination and modulated overall by the PSF of the individual subapertures

For uniform intensity with Gaussian random piston phase and no tilt:

$$I(\vec{x},0)=\frac{P}{A}\left\{\left|\sum_{n=1}^{N}e^{i\frac{2\pi}{\lambda z}\vec{x}.\vec{\xi}}\right|^2 e^{-\sigma_\varphi^2}+N\left(1-e^{-\sigma_\varphi^2}\right)\right\}\left|\frac{1}{\lambda z}\iint e^{i\frac{2\pi}{\lambda z}\vec{x}.\vec{\rho}}\,d^2\vec{\rho}\right|^2$$

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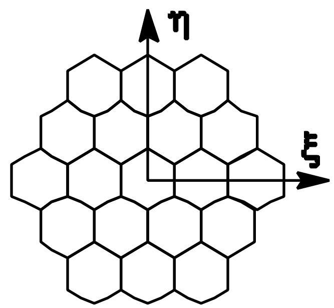
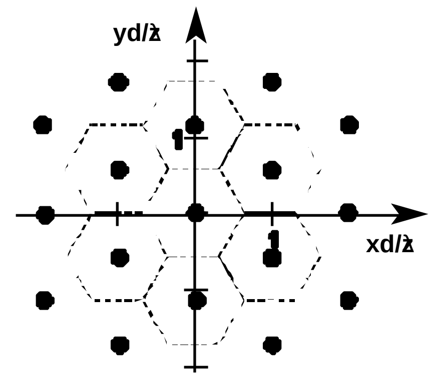
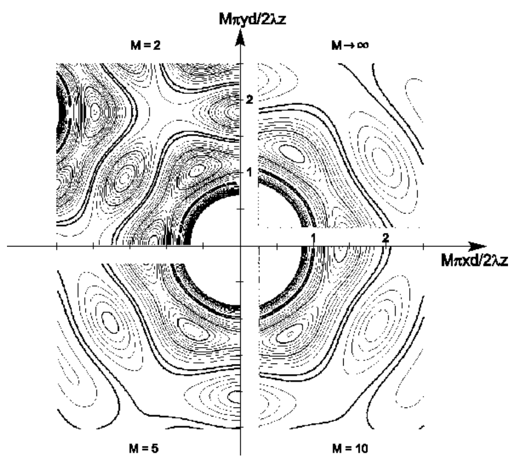
Hexagonal Spacing

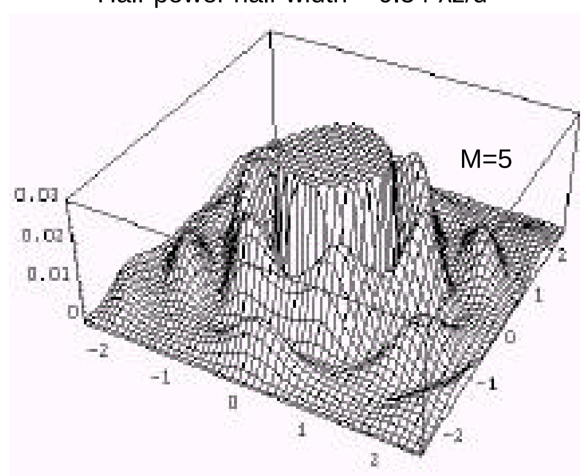




M = 2 rings, N = 19 segments
N = 3M(M+1)+1

Peak spacing = 2/ 3 λz/d
Half-power half-width = 0.54 λz/d





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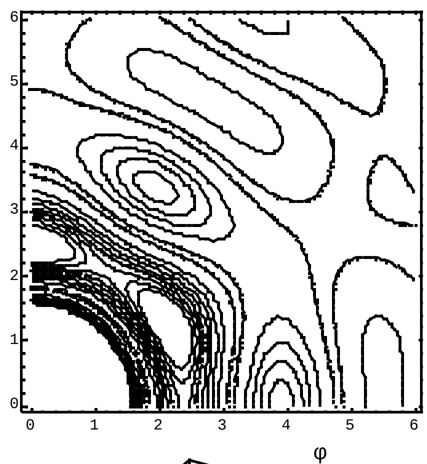
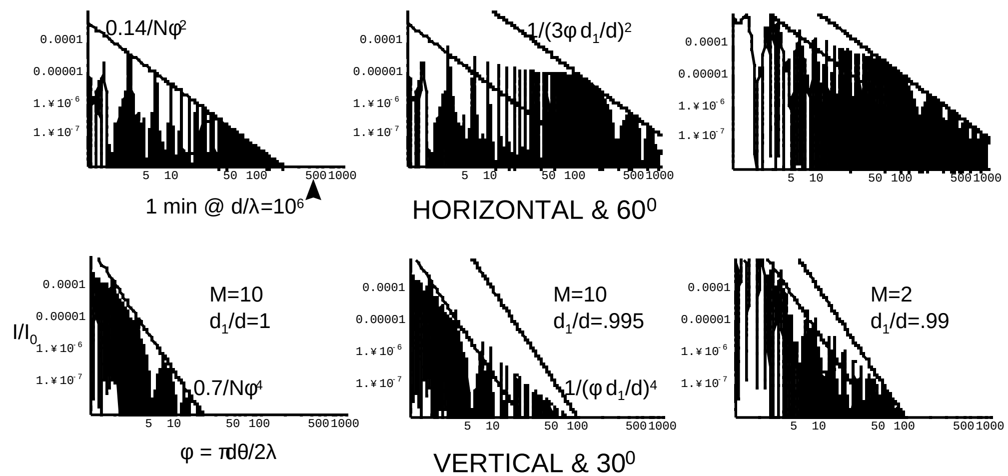
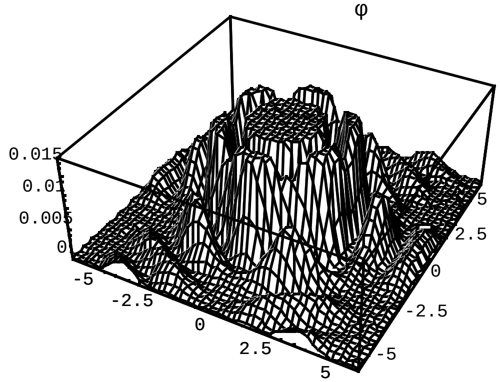
Hexagonal Segments







Peaks at large angles determined by segments and gaps, not by array

Horizontal decay as $1/(\theta\ d_1/d)^2$, vertical as $1/(\theta\ d_1/d)^4$

Frequency of peaks proportional to gap size

Small gaps simply shift artifacts from central axis

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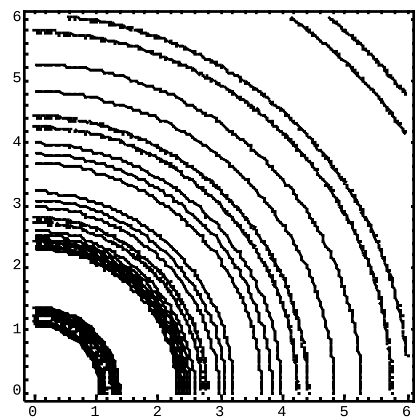
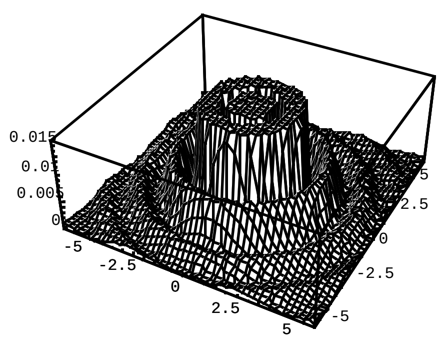
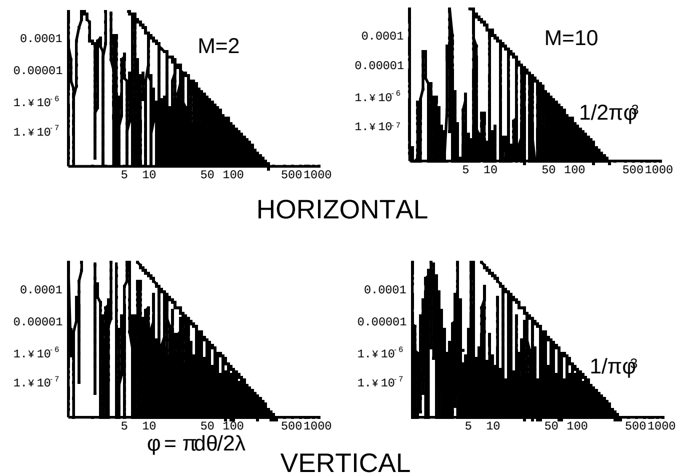
Circular Segments







Close-packed circular segments on a hexagonal grid suffer 9.3% power and 17.8% peak intensity penalties, but far-field is much more symmetric, and artifacts decay as 1/θ^3

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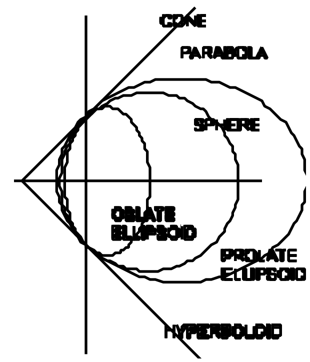
Optimum Correctors with a Spherical Primary



$$z = [1 + \psi(r/4F)^2 + \ldots]/4F$$

ψ= aparabolic deformation constant (e.g., 0 for parabola, and 1 for sphere)

Reimaging configuration

For local reimaging with axial incidence, OPD vanishes through 6th order for ψ_2 = 1.66 (oblate ellipsoid secondary) and ψ_3 = -24.1 (hyperboloid tertiary) for M=10 with tertiary at internal focus

Non-Reimaging Configuration

With off-axis operation, lowest-order spherical aberration and coma vanish for ψ_2 = -0.100 (nearly-parabolic hyperboloid secondary) and ψ_3 = 6.95 (oblate ellipsoid tertiary) for M = f = 10 with tertiary at internal focus

Need one surface for each corrected aberration

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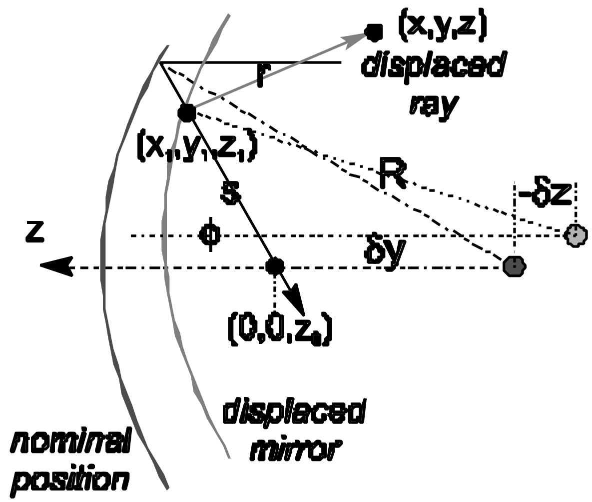
Alignment Tolerances with a Spherical Primary



Paraxial ray analysis with small f (high f#) gives

$$\Delta S^2_{RMS} = [\frac{9}{8}\left(\frac{\delta_y^2}{R}\right)^2 + \left(\frac{\delta_y^2}{R} - \delta_z\right)^2]/[\,48(2f)^2]$$

For ΔS_{MAX} = 0.1μ (λ/20 @ 2μ), f = 1.5, and D = 20 m:

$(\delta_y)_{MAX}$ =4.36f (ΔS_{MAX}R) = 16 mm

$(\delta_z)_{MAX}$ = 16 3 ΔS_{MAX} f^2 = 6.2μ

A small allowable axial error (microns) with a large allowable transverse error (millimeters) will be characteristic of all such systems where a large spherical primary can shift relative to the rest of the system

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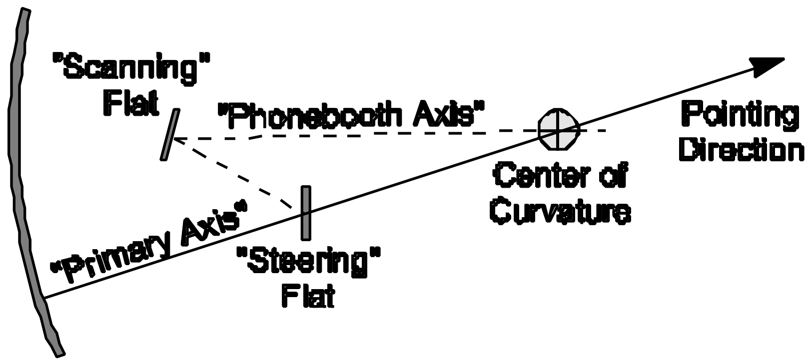
Auxiliary Optics

Auxiliary set of flat mirrors can correct all global misalignments

Internal focus allows very small elements

Spherical primary can provide wide-angle pointing capability and/or focal plane scanning without large-body motion



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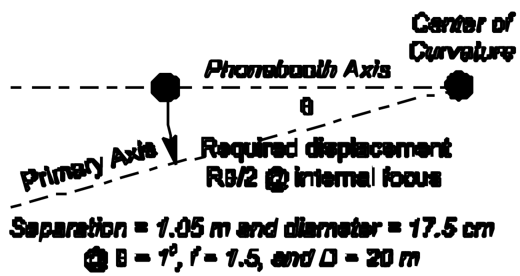
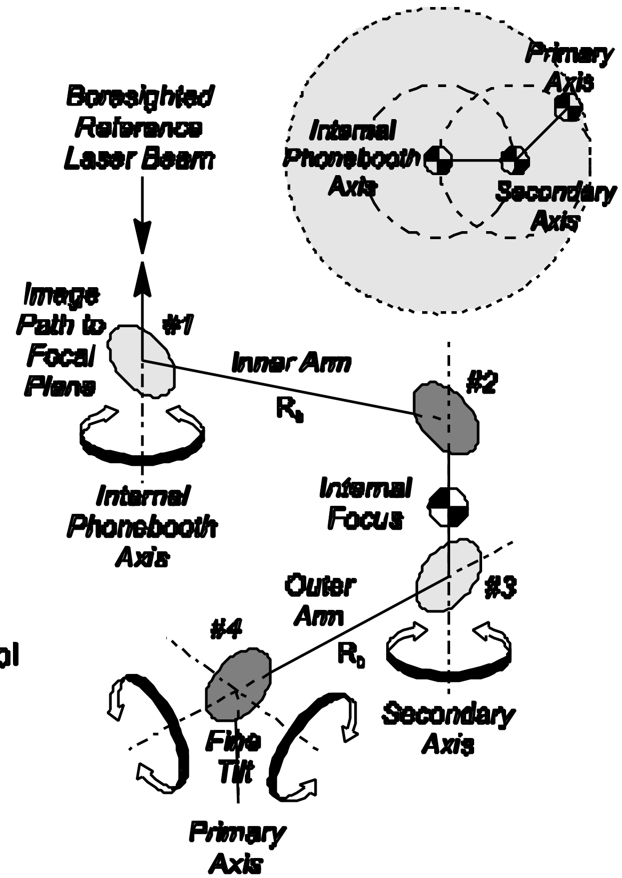
Dynamic Module for Alignment/Pointing/Scanning





- Continuous displacement from 0 to $2R_a$
- No on-axis "blind spot"
- Axial spacing maintained, precision control by out-of-plane translation of any mirror
- No image rotation
- Maximum mirror size $\approx \sqrt{2}R_o/f = \theta D/\sqrt{2}$

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Conclusion

Attractive concept for very large space telescope:

- Two-module configuration
- Spherical primary mirror with replicated mirror segments
- Corrective tertiary with active APS at internal focus